

Medium Modification of γ -jets in High-energy Heavy-ion Collisions

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(Dated: February 26, 2013)

Medium modification of γ -tagged jets in high-energy heavy-ion collisions is investigated within a Linearized Boltzmann Transport model for jet propagation that includes both elastic parton scattering and induced gluon emission. Inclusion of recoiled medium partons in the reconstruction of partonic jets is found to significantly reduce the net jet energy loss. Experimental data on γ -jet asymmetry and survival rate in Pb + Pb collisions at $\sqrt{s} = 2.76$ TeV can be reproduced. Medium modifications of reconstructed jet fragmentation function, transverse profile and energy flow outside the jet-cone are found to be sizable especially for γ -tagged jets with small values of $x = p_T^{\text{jet}}/p_T^\gamma$.

PACS numbers: 25.75.-q, 25.75.Bh, 25.75.Cj, 25.75.Ld

Jet quenching [1], caused by jet-medium interaction and manifested in the suppression of large p_T hadron spectra, dihadron and γ -hadron correlation, has been used successfully to probe properties of quark-gluon plasma in high-energy heavy-ion collisions. The study has been extended to reconstructed jets [2] which are less sensitive to the non-perturbative process of hadronization. Large dijet asymmetry in central Pb + Pb collisions at $\sqrt{s} = 2.76$ TeV is indeed observed at the Large Hadron Collider (LHC) [3]. Further studies of experimental data within models of jet propagation [4–7] can yield information on the strength of jet-medium interaction and transport properties of the quark-gluon plasma.

A jet in the partonic picture contains many shower partons from the final-state radiation of the leading parton. These shower partons will interact with the thermal medium and lead to parton energy loss, transverse momentum broadening and modification of the jet shape. Transport of the recoiled thermal partons from jet-medium interaction, on the other hand, can also lead to jet-induced medium excitation [8]. Jets in heavy-ion experiments are reconstructed with a jet-finding algorithm [9] and consist of collimated clusters of hadrons within a jet-cone $\sqrt{(\phi - \phi_C)^2 + (\eta - \eta_C)^2} \leq R$, where η and ϕ are hadrons' pseudo-rapidity and azimuthal angle, respectively, and the subscript C denotes the center of the jet-cone. Energy within the jet-cone should contain hadrons from both shower and recoiled thermal partons. It is therefore important to analyze experimental data taking into account of both medium-modified shower parton distributions and jet-induced medium excitation.

Back-to-back γ -jets are considered “golden channels” for the study of jet quenching since they are free of trigger bias [10] as compared to dijets. Though γ -jet asymmetry as measured in Pb + Pb collisions at LHC [11, 12] can be explained by parton energy loss [13, 14], no attention has been paid to the effect of jet-induced medium excitation. In this Letter, we will report a first study of medium mod-

ification of γ -tagged jets in high-energy heavy-ion collisions within a Linearized Boltzmann Transport (LBT) model [15] which tracks the transport of both shower and recoiled medium partons. We will focus particularly on the effect of jet-induced medium excitation on jet energy loss, modification of jet profiles and energy flow outside the jet-cone. We further study the dependence of jet profile on jet propagation length by selecting jets with different γ -jet asymmetry.

Within the LBT model, propagation of jet shower partons and medium excitation is simulated according to a linearized Boltzmann equation,

$$p_1 \cdot \partial f_1(p_1) = - \int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4) |M_{12 \rightarrow 34}|^2 \times (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4), \quad (1)$$

where $dp_i = d^3p_i/[2E_i(2\pi)^3]$, $f_i = 1/(e^{p \cdot u/T} \pm 1)$ ($i = 2, 4$) are parton phase-space distributions in a thermal medium with local temperature T and fluid velocity $u = (1, \vec{v})/\sqrt{1 - \vec{v}^2}$, $f_i = (2\pi)^3 \delta^3(\vec{p} - \vec{p}_i) \delta^3(\vec{x} - \vec{x}_i - \vec{v}_i t)$ ($i = 1, 3$) are the parton phase-space densities before and after scattering. We assume small angle approximation for the elastic scattering amplitude $|M_{12 \rightarrow 34}|^2 = Cg^4(\hat{s}^2 + \hat{u}^2)/(-\hat{t} + \mu_D^2)^2$ with Debye screening mass μ_D , where \hat{s} , \hat{t} , and \hat{u} are Mandelstam variables, and $C=1$ (9/4) is the color factor for quark-gluon (gluon-gluon) scattering. The strong coupling constant $\alpha_s = g^2/4\pi$ is fixed and will be determined via comparison to experimental data.

Partons are assumed to propagate along classical trajectories between two adjacent collisions. The probability of scattering is determined in each time step Δt by $P_a = 1 - \exp[-\sum_j (\Delta x_j \cdot u) \sum_b \sigma_{ab} \rho_b(x_j)]$, where σ_{ab} is the parton scattering cross section, the sum over time steps starts from the last scattering point, and ρ_b is the local medium parton density. Both shower (p_3) and recoiled medium partons (p_4) after each scattering are followed by further scatterings in the medium. To account for the back-reaction in the Boltzmann transport, initial

thermal partons (p_2), denoted as “negative” partons, are transported according to the Boltzmann equation. Their energies and momenta will be subtracted from all final observables. These “negative” partons are considered as part of the recoiled partons that are responsible for jet-induced medium excitations [15].

In this study, the LBT is extended to include induced radiation accompanying each elastic scattering according to the high-twist approach [16],

$$\frac{dN_g^a}{dz dk_\perp^2 dt} = \frac{6\alpha_s P(z)}{\pi k_\perp^4} (\hat{p} \cdot u) \hat{q}_a \sin^2 \frac{t - t_i}{2\tau_f}, \quad (2)$$

where z and k_\perp are the energy fraction and transverse momentum of the radiated gluon, $\hat{p}_\mu = p_\mu/p_0$, $P(z) = [1 + (1-z)^2]/z$ the splitting function, $\tau_f = 2Ez(1-z)/k_\perp^2$ the gluon formation time, and $\hat{q}_a = \sum_b \rho_b \int d\hat{t} q_\perp^2 d\sigma_{ab}/d\hat{t}$ the jet transport parameter. The Debye screening mass μ_D is used as an infrared cut-off for the gluon’s energy. Multiple gluon emission induced by a single scattering is included according to a Poisson distribution. All radiated gluons are assumed to be on-shell and their 4-momenta are successively determined from Eq. (2). The first radiated gluon is assumed to be associated with the current scattering with given transverse momentum transfer. The 4-momenta of the final beam and recoiled parton are determined according to a $2 \rightarrow 3$ process. The next gluon emission is carried out by setting the final beam parton of the previous gluon emission off-shell with its large component of the light-cone momentum unchanged. The transverse momentum of the previous emitted gluon will be reset by its on-shell condition and 4-momentum conservation of the current gluon emission. Such procedure can be repeated for the rest of N_g gluon emissions.

For initial configurations of γ -jets, we use HIJING [17] for $p + p$ collisions at $\sqrt{s} = 2.76$ TeV with a trigger on the transverse momentum transfer $q_T \geq 30$ GeV in the CM frame of two colliding partons. Further selections are made for events with $p_T^\gamma > 60$ GeV. Jet shower partons, including those from both initial and final-state radiation, are transported through a thermal medium within the LBT model. The final partons, including “negative” partons, are used for jet reconstruction using a modified version of the anti- k_t algorithm in FASTJET [9], in which energies and momenta of “negative” partons are subtracted from the final jet observables. Energies of jets reconstructed from final hadrons and partons differ only about 1 GeV in $p + p$ collisions from HIJING.

To illustrate the influence of jet-induced medium excitation on the final jet energy, we consider first the propagation of γ -tagged jets in a uniform and static gluonic medium at temperature $T = 300$ MeV. We set $\alpha_s = 0.4$ and $\mu_D^2 = 1$ GeV² for simplicity and use a jet-cone size $R = 0.4$. Shown in Fig. 1(a) is the net jet energy loss as a function of the propagation time. If we include only jet shower partons (dotted) in the jet reconstruction, the energy loss is considerably larger than when radiated gluons

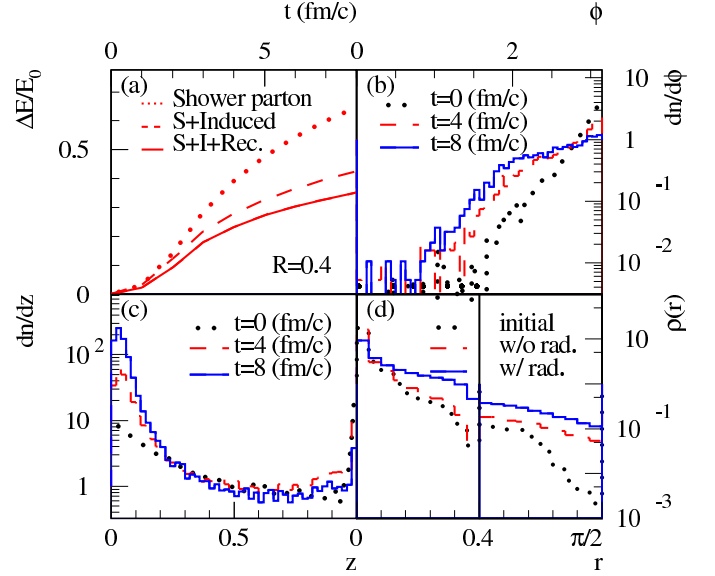


FIG. 1: (a) Energy loss as a function of time; (b) azimuthal distribution relative to the γ -direction, (c) reconstructed jet fragmentation function (parton) at different times, (d) initial (dotted) and final jet transverse profile with (solid) and without (dashed) induced radiation for γ -tagged jets in a uniform gluonic medium. See text for more detailed descriptions.

(dashed) or all (shower + radiated + recoiled) partons (solid) are included. Therefore, both radiated gluons and recoiled partons from the elastic scattering enter the jet-cone and become part of the reconstructed jets. The net jet energy loss shows a clear quadratic time-dependence during the early times. The reconstructed jets also show significant deflection with respect to the γ -direction at later times due to jet-medium interaction as shown in Fig. 1(b). Shown in Fig. 1(c) is the longitudinal momentum fraction ($z = p_L/E^{\text{jet}}$) distribution, which we will refer to as reconstructed jet fragmentation function, of partons within the jet-cone at different times. There is very little change at large and intermediate z , but huge enhancement at low z due to contributions from recoiled partons and radiated gluons. In Fig. 1(d) we show the jet transverse profile,

$$\rho(r) = \frac{1}{\Delta r} \frac{1}{N^{\text{jet}}} \sum_{\text{jets}} \frac{p_T(r - \Delta r/2, r + \Delta r/2)}{p_T(0, R)}, \quad (3)$$

of the initial jet (dotted) and at a later time $t = 8$ fm/c (solid and dashed), where $p_T(r_1, r_2)$ is the summed p_T of all partons in the annulus between radius r_1 and r_2 inside the jet-cone. We also extend the above transverse energy profile to outside the jet-cone between $R < r < \pi/2$. Without induced gluon radiation, elastic scatterings have little effect on the jet transverse profile within the jet-cone while recoiled partons contribute to transverse energy flow outside the cone. Induced gluon radiation, on the other hand, significantly broadens the transverse energy profile both within and outside the jet-cone.

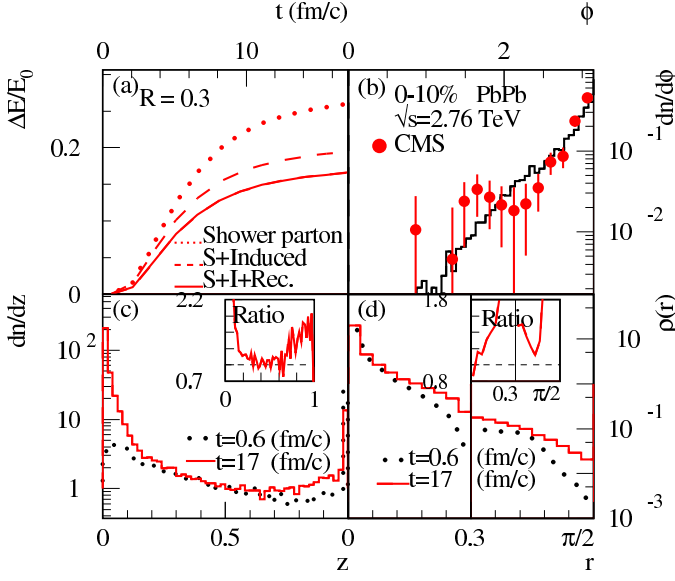


FIG. 2: The same as Fig. 1, except in central (0-10%) Pb + Pb collisions at $\sqrt{s} = 2.76$ TeV. The inserts in (c) and (d) are ratios of initial and final reconstructed jet fragmentation functions (parton) and transverse profiles, respectively. See text for detailed descriptions.

To study the effect of jet energy loss and medium modification of γ -tagged jets in heavy-ion collisions within LBT model, we use the space-time profile of temperature and fluid velocity in the quark-gluon phase from (3+1)D ideal hydrodynamical simulations [18] of Pb + Pb collisions at the LHC. The initial γ -jet production from HIJING is distributed according to the overlap function of two colliding nuclei with a Wood-Saxon nuclear geometry. Whenever comparisons are made to the experimental data, we apply the same kinematic cuts to LBT results. For CMS data [11], $p_T^\gamma > 60$ GeV, $|\eta^\gamma| < 1.44$, $p_T^{\text{jet}} > 30$ GeV, $|\eta^{\text{jet}}| < 1.6$, and $\Delta\phi = |\phi^{\text{jet}} - \phi^\gamma| > 7\pi/8$; and for ATLAS data [12], $60 < p_T^\gamma < 90$ GeV, $|\eta^\gamma| < 1.3$, $p_T^{\text{jet}} > 25$ GeV, $|\eta^{\text{jet}}| < 2.1$, and $\Delta\phi > 7\pi/8$. In LBT simulations, we use a Debye screening mass $\mu_D^2 = 4\pi\alpha_s T^2$.

Shown in Fig. 2(a) is the averaged jet energy loss as a function of time in the most 10% central Pb + Pb collisions at $\sqrt{s} = 2.76$ TeV for a jet cone-size $R = 0.3$ from LBT simulations with $\alpha_s = 0.2$. Similar to the results in a uniform medium in Fig. 1(a), inclusion of recoiled partons (solid) significantly reduces the net jet energy loss as compared to the case when only shower partons (dotted) and radiated gluons (dashed) are included in the jet reconstruction. Because of rapid expansion and cooling of the thermal medium, jet energy loss saturates approximately 10 fm/c after an initial linear rise. For the same reason the jet azimuthal distribution as shown Fig. 2(b) remains almost unchanged as compared to that in p + p collisions, in agreement with CMS data [11]. Modification of the reconstructed jet fragmentation function in

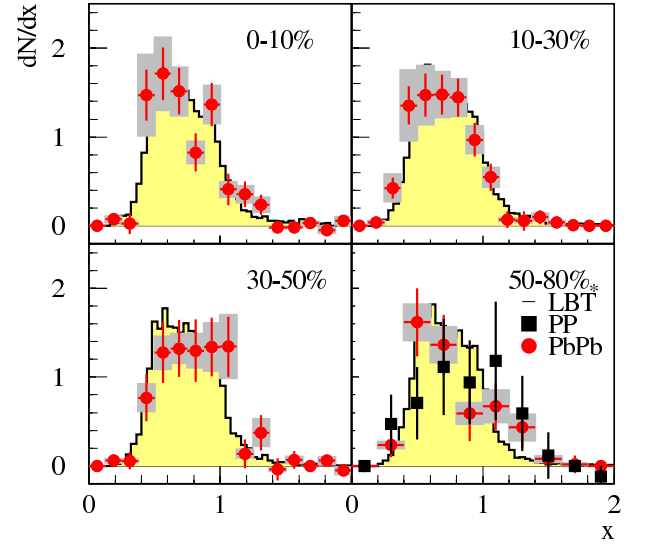


FIG. 3: Distribution of γ -jet asymmetry $x = p_T^{\text{jet}}/p_T^\gamma$ in Pb + Pb collisions with four centralities at $\sqrt{s} = 2.76$ TeV from LBT with $\alpha_s = 0.2$ as compared to CMS data [11].

Fig. 2(c) is also very small at large and intermediate z region but sees big enhancement at small z due mostly to contributions from radiated gluons. The jet transverse profile shown in Fig. 2(d) is enhanced by 40% around the edge both inside and outside the jet-cone. The jet transverse profile outside the jet-cone are also enhanced due to dissipation of the lost jet energy that are carried by recoiled partons and radiated gluons. Similar features have been observed in single jets in central Pb + Pb collisions at LHC [19].

Following experiments at LHC [11, 12], one can study the effect of jet energy loss on the γ -jet asymmetry distribution, dN/dx with $x = p_T^{\text{jet}}/p_T^\gamma$. Shown in Fig. 3 are γ -jet asymmetry distributions from LBT simulations (histogram) as compared to CMS data [11] in Pb + Pb collisions with four different centralities. Because of initial-state radiation, γ -jets are produced with large momentum asymmetry in both p + p and peripheral heavy-ion collisions where jet energy loss is small. The asymmetry distributions are, however, skewed to smaller values of x in central heavy-ion collisions due to jet energy loss as seen in the LBT results which can fit the experimental data quite well with a fixed value of $\alpha_s = 0.2$.

We can further quantify the γ -jet asymmetry in heavy-ion collisions by the averaged asymmetry or ratio of the jet and photon transverse momenta $\langle x \rangle = \langle p_T^{\text{jet}}/p_T^\gamma \rangle$ and the jet survival rate or fraction of γ -tagged jets $R_{J\gamma}$ with $p_T^{\text{jet}} > 30$ GeV (CMS cut) or $x = p_T^{\text{jet}}/p_T^\gamma > 0.42$ (ATLAS cut). Shown in Fig. 4 are LBT results (lines) on the averaged γ -jet asymmetry $\langle x \rangle$ and jet survival rate $R_{J\gamma}$ as functions of the number of participant nucleons are compared to CMS (solid circle and square) [11] and ATLAS (open circle) data [12]. Note that kinematic cuts

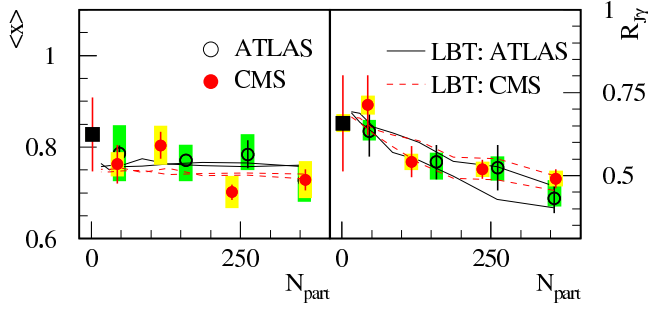


FIG. 4: Averaged γ -jet asymmetry $\langle x \rangle = \langle p_T^{\text{jet}}/p_T^\gamma \rangle$ (left) and jet survival rate $R_{J\gamma}$ (right) as functions of the number of participant nucleons in Pb+Pb at $\sqrt{s} = 2.76$ TeV from LBT as compared to experimental data [11, 12]. Values of $\alpha_s = 0.15 - 0.23$ (dashed) and $0.2 - 0.27$ (solid) are used for LBT calculations with CMS and ATLAS cuts, respectively.

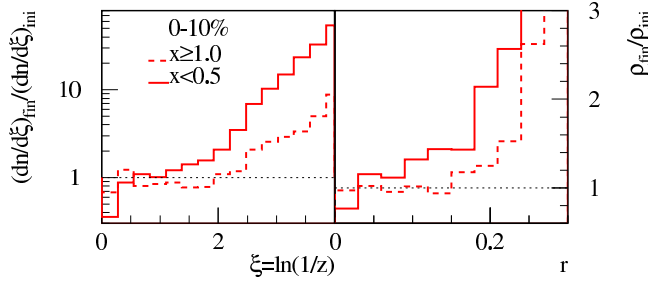


FIG. 5: Medium modification of the reconstructed jet fragmentation function (parton) (left) and transverse profile (right) with momentum asymmetry $x < 0.5$ (solid) and $x > 1.0$ (dashed) for γ -tagged jets in central (0-10%) Pb + Pb collisions at $\sqrt{s} = 2.76$ TeV.

in ATLAS data, which are also truncated with $x < 0.42$, are somewhat different from that in CMS data. In LBT calculations, $\alpha_s = 0.15-0.23$ are used with the CMS cuts (dashed) while $\alpha_s = 0.2-0.27$ for the ATLAS cuts (solid). One can see that the averaged momentum asymmetry $\langle x \rangle$ has a very weak centrality dependence and is not very sensitive to the value of α_s . The jet survival rate $R_{J\gamma}$ has, however, a stronger dependence on the centrality and the value of α_s or strength of jet-medium interaction.

Since smaller values of $x = p_T^{\text{jet}}/p_T^\gamma$ imply larger average jet energy loss, one should expect stronger medium modification of γ -tagged jets. This is indeed the case as seen in Fig. 5, where we show medium modification of the reconstructed jet fragmentation function for partons (left) and transverse profile (right) for γ -tagged jets with different values of x . The reconstructed jet fragmentation function at low z and transverse profile toward the edge of the jet-cone are both significantly enhanced for events with $x < 0.5$. One should expect to see larger enhancement for smaller values of x which can be achieved by increasing the energy of the triggered γ .

In summary, we have studied medium modification of γ -tagged jets in high-energy heavy-ion collisions within

the LBT model that can reproduce well recent experimental data on γ -jet asymmetry and survival rate in Pb + Pb collisions at LHC. Inclusion of recoiled medium partons in the jet reconstruction is found to lead to significant reduction in net jet energy loss therefore should be taken into account in model studies. No jet deflection are observed and medium modification of the reconstructed jet fragmentation function and transverse profile are also quite modest because of the short averaged path length in an expanding system. By selecting events with small values of $x = p_T^{\text{jet}}/p_T^\gamma$, one can focus on jets with large energy loss and therefore will see much stronger medium modification. Such approach can help to achieve more detailed jet tomography of the quark-gluon plasma in high-energy heavy-ion collisions.

We thank M. Cacciari for providing a modified version of FASTJET for use in this study. This work is supported by the NSFC under grant No. 11221504, U.S. DOE under Contract No. DE-AC02-05CH11231 and within the framework of the JET Collaboration. YZ is also supported by the German Research Foundation DFG (ITRG) GRK 881 and the Humboldt Foundation.

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- [1] X. -N. Wang and M. Gyulassy, Phys. Rev. Lett. **68**, 1480 (1992).
 - [2] I. Vitev and B. -W. Zhang, Phys. Rev. Lett. **104**, 132001 (2010).
 - [3] G. Aad *et al.* [Atlas Collaboration], Phys. Rev. Lett. **105**, 252303 (2010).
 - [4] G. -Y. Qin and B. Muller, Phys. Rev. Lett. **106**, 162302 (2011).
 - [5] C. Young, B. Schenke, S. Jeon and C. Gale, Phys. Rev. C **84**, 024907 (2011).
 - [6] Y. He, I. Vitev and B. -W. Zhang, Phys. Lett. B **713**, 224 (2012).
 - [7] T. Renk, Phys. Rev. C **85**, 064908 (2012).
 - [8] J. Casalderrey-Solana, E. V. Shuryak and D. Teaney, J. Phys. Conf. Ser. **27**, 22 (2005).
 - [9] M. Cacciari, G. P. Salam and G. Soyez, Eur. Phys. J. C **72**, 1896 (2012).
 - [10] X. -N. Wang, Z. Huang and I. Sarcevic, Phys. Rev. Lett. **77**, 231 (1996); H. Zhang, J. F. Owens, E. Wang and X. -N. Wang, Phys. Rev. Lett. **103**, 032302 (2009).
 - [11] S. Chatrchyan *et al.* [CMS Collab.], arXiv:1205.0206.
 - [12] [ATLAS Collaboration], ATLAS-CONF-2012-121.
 - [13] W. Dai, I. Vitev and B. -W. Zhang, arXiv:1207.5177.
 - [14] G. -Y. Qin, arXiv:1210.6610.
 - [15] H. Li, F. Liu, G. -L. Ma, X. -N. Wang and Y. Zhu, Phys. Rev. Lett. **106**, 012301 (2011).
 - [16] X. -N. Wang and X. -F. Guo, Nucl. Phys. A **696**, 788 (2001).
 - [17] X. -N. Wang and M. Gyulassy, Phys. Rev. D **44**, 3501 (1991).
 - [18] T. Hirano, U. W. Heinz, D. Kharzeev, R. Lacey and Y. Nara, Phys. Lett. B **636**, 299 (2006).
 - [19] [CMS Collaboration], CMS-PAS-HIN-12-013.